Report for 2002AK1B: Investigation of Immiscible Fluid Movement Through Frozen Porous Media

- Articles in Refereed Scientific Journals:
  - Barnes, D.L., S.M. Wolfe, and D.M. Filler. Equilibrium Distribution of Petroleum Hydrocarbons in Freezing Ground. In Review, Polar Record.
  - Barnes, D. L. and D. M. Filler. 2003. Spill Evaluation of Petroleum Products in Freezing Ground. Polar Record, 39 no. 210: 1-6.
- Conference Proceedings:
  - Wolfe, S. M., D. L. Barnes, Y. Shur, and D. M. Filler. 2003. Two-Dimensional Movement of Immiscible Fluids Through Frozen Soil. In Proceedings of the 3rd Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, May 5-6, 2003.

Report Follows:

Introduction

Frequent releases of petroleum in regions experiencing seasonal or permanent frozen ground has prompted engineers and scientists to investigate the physical and chemical aspects of immiscible fluid movement in frozen ground. An understanding of these processes is required to engineer methods for protecting both the environment and human health. In Alaska, several recent relatively large petroleum releases in areas of permanently and seasonally frozen ground illustrates the importance of gaining a better understanding of the physical and chemical processes controlling the migration of these compounds through frozen ground to possible freshwater sources.

One key facet of this topic is the relationship between structures of frozen soil (cryogenic structures), moisture content (frozen and unfrozen) and the permeability of soil to petroleum products. It is known that freezing and thawing are very important factors of soil structure. Freezing and ice formation produce cryogenic structure and desiccation of soil below freezing front leads to shrinkage and cracking of soil. Thawing of frozen soil and melting of ice inclusions does not completely destroy soil structure formed during freezing. So-called post-cryogenic structure is the structure of thawed soil affected by freezing and thawing. Such structure makes soil of the active layer highly permeable especially in horizontal direction. Proper cleanup response to petroleum releases requires a good understanding of how these cryogenic processes will affect petroleum migration through the subsurface. Currently little is known on this subject. Critical questions such as how does pore ice influence the lateral and vertical migration of petroleum, how does soil-water content prior to freezing influence the migration of petroleum, and how do the physical and chemical properties of petroleum hydrocarbon influence the migration? This study is producing results that help answer these relevant questions.

Problem & Research Objectives

The objective of this research is to gain a better understanding of how the movement of immiscible fluids, specifically petroleum hydrocarbons, through porous media is influenced by seasonal freezing. This objective is being accomplished through laboratory testing and quantitative analysis.

To study contaminant movement in freezing soil it is important to recognize the main patterns of frozen media:

The frozen active layer above unfrozen soil;
The frozen active layer above permafrost;
The unfrozen active layer above permafrost.

Permeability (saturation) of permafrost depends on soil genesis, soil type, and genesis of permafrost (syngenetic or epigenetic). Soil of the same type can be practically unsaturated or even over saturated with ice depending on a genesis of permafrost.

The structure of the active layer is greatly dependent upon the freezing system (open or closed). The active layer over permafrost is usually formed in the closed system. In areas of cold permafrost where soil in the active layer freezes downward from the surface and upward from the bottom of the permafrost table, upper and lower part of the active layer can be saturated with ice and middle part of the active layer is dry and has high open porosity due to vertical and horizontal cracks. In areas of warm permafrost, freezing proceeds only downward from the surface and ice saturated upper part of the active layer is often underlain by dry soil with cracks. Also thickness of saturated soil depends on numerous factors, there are several general patterns in soil structure in the active layer and permafrost which study can provide understanding of permeability of frozen soil. All of these effects influence the lateral and vertical movement of petroleum product that is inadvertently released to frozen soils. We are developing a better understanding of how pore ice influences this movement by using laboratory scale soil flumes performing laboratory studies on the movement of petroleum through frozen soil. Characteristics of petroleum hydrocarbons through unsaturated soils and their fate in the subsurface have been under study for several decades. Many definitive manuscripts have been written that describe the physical and chemical fate of these compounds in soils that do not experience temperatures below zero degrees Celsius. However, little is known about the chemical fate of these compounds in soils that experience seasonal freezing and thawing. Chemical fate in this study is defined as the partitioning between the volatile, dissolved, adsorbed, and liquid fractions in unsaturated soils. The relative fraction of each of these different phases influences the gaseous phase, aqueous phase, and liquid phase migration of petroleum hydrocarbons. A quantitative analysis of phase partitioning in freeze susceptible soils is used in this study to better understand the influence freezing has on the chemical and physical fate of petroleum hydrocarbons in soil.

Methodology

The laboratory flumes used for this study were designed and constructed after extensive literature review on the topic of immiscible fluid migration in soils (Figure 1). Two flumes were constructed. To investigate how pore ice impacts the migration of petroleum hydrocarbons the flume will be filled and compacted with sand wetted to uniform water content and placed in the cold room at a temperature of approximately -5^{o} C. The properties of the sand (water retention characteristics, permeability, porosity, density) are measured in the laboratory. Colored petroleum is introduced into the column. Progression of the resulting immiscible fluid plume is tracked using time-lapse photography. Several initial water contents (prior to freezing) are been investigated.

Figure 1. Soil flumes for frozen ground study

Principal Findings to Date and Significance

Several migration tests have been conducted. Two of these tests are reported here. The two tests differed in water content, with one test having roughly twice the water content as the other. Colored petroleum (100 ml) was introduced into the frozen sand in each flume. The progression of the petroleum was monitored over time. Figures 2 shows the resulting plumes at approximately 18.5 hours.

Figure 2. Plume shapes after approximately 18.5 hours for two flumes. The flume on the right has twice the water content prior to freezing as the plume on the left.

In Figure 2, note the increased lateral spread of petroleum in the flume containing the higher water content (flume on the right side of the figure). The increased capillary forces due to the increased pore ice are evident in this flume in comparison to the plume shape in the flume with half the initial water content. Field studies also show the influence of increased capillary forces due to pore ice. A manuscript detailing this field study has been accepted for publication in the Journal *Polar Record*. Future laboratory tests will include conducting similar tests with a different gradation of sand.

So far laboratory tests and field studies designed to allow us to gain a better understanding of the mechanisms that control plume migration into a frozen sand have been discussed. Once petroleum hydrocarbon has been introduced into soil, the chemical and physical fate of the contaminant during cyclic freeze thaw processes is also of interest. Past documented laboratory measurements have shown movement of petroleum hydrocarbons to the freezing front in contaminated freezing soils. The mechanisms that are, in part, responsible for the increased contaminant concentration at the freezing front are illustrated in this study with a mass balance model. Results developed in this study show that this concentration increase is due to exclusion of petroleum hydrocarbon from the crystalline ice structure and from physical displacement of liquid petroleum hydrocarbon from the pore space as water freezes and expands into ice. A manuscript discussing this model and the results has been submitted to *Polar Record* for peer review.